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# Assessing impacts of future potential climate change scenarios on aquifer recharge in continental Spain

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ABSTRACT

Climate change will modify the availability of groundwater resources in the future. Thus the evaluation of average aquifer recharge from precipitation, and its uncertainty, becomes a key subject in determining suitable countrywide water policies. The confident prediction of renewable groundwater resources requires an accurate evaluation of aquifer recharge over time and space, especially in large territories with varied conditions for aquifer recharge such as continental Spain. This study asses impacts of future potential climatic change scenarios on distributed net aquifer recharge (NAR) from precipitation over continental Spain. For this, the used method (1) generates future time series of climatic variables (precipitation, temperature) spatially distributed over the territory for potential aquifer recharge (PAR), and (2) simulates them within previously calibrated spatial PAR or NAR recharge models from the available historical information to provide distributed PAR or NAR time series. The information employed comes from the Spain02 project for the historical climatic data, from Alcalá and Custodio (2014, 2015) for the historical spatial NAR, and from the CORDEX EU project (2013) regional climate models (RCMs) simulations for the future climate scenarios. A distributed empirical precipitation-recharge model is defined by using a regular 10 km × 10 km grid, and assuming that precipitation (P) and temperature (T) are the most important climatic variables determining PAR, while their spatiotemporal variabilities determine the impacts of future potential climatic scenarios on renewable groundwater resources. Potential plausible pictures of future climate scenarios are defined by combining information coming from different RCMs and General Circulation models (GCMs), downscaling techniques, and ensemble hypothesis. These scenarios were simulated within the used precipitation-recharge model to estimate impacts on NAR. The results show that global mean NAR decreases by 12% on average over continental Spain. Over 99.8% of the territory, a variable degree of recharge reduction is obtained; the reduction is quite heterogeneously distributed in line with the variety of conditions for aquifer recharge over continental Spain. The standard deviation of annual mean NAR will increase by 8% on average in the future. The dependence of these changes regarding potential explanatory variables, such as elevation and latitude was also analysed.


## 1. Introduction

The evaluation of aquifer recharge from precipitation is essential to make a quantitative evaluation of renewable groundwater resources, required to implement appropriate countrywide water policies (Freeze and Cherry, 1979; National Ground Water Association, 2004). Potential and net aquifer recharge can be evaluated. From a hydrological point of view, 'potential' aquifer recharge (PAR) refers to the fraction of precipitation (P) that infiltrates into the soil and percolates below the root zone. It is expected to be greater than 'net' aquifer recharge (NAR) (De Vries and Simmers, 2002; Andreu et al., 2011; España et al., 2013), which is the fraction of recharge that reaches the water table after some delay, smoothing out the variability inherent to precipitation events (Lerner et al., 1990; Batelaan and de Smedt, 2007). Note that precipitation events include all the atmospheric water phases reaching the land surface, such as rain, snow, dew, fog, etc. For the purpose of assessing renewable groundwater resources, the NAR fraction is what matters (Alcalá and Custodio, 2014).

Aquifer recharge evaluation is a complex task subjected to significant uncertainties inferred by governing weather and physical

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variables, as well as the choosing of appropriate techniques to cover different physical processes determining recharge (Milly and Eagleson, 1987; De Vries and Simmers, 2002; Clark et al., 2011). Aquifer recharge varies over space and time. So, the NAR timing may vary from daily to weekly when the water table is shallow (Andreu et al., 2011) to monthly to yearly in areas having a thick vadose zone (Alcalá et al., 2011). For example, the snow melting seasonal cycles may determine recharge rates and timing in mountainous areas (Simpson et al., 1972; Winograd et al., 1998; Earman et al., 2006).

The complexity of aquifer recharge evaluation increases when we intend to estimate potential impacts of long-term climate variability. Aquifer recharge may be subjected to variation due to global driving forces such as climate change and local human actions such as land-use transitions, and this adds to the overall uncertainty in planning future evaluations under different climate scenarios. The main statistics (mean and standard deviation) of natural recharge from precipitation over a long enough period should not change substantially, unless they were influenced by climate or land-use changes. The steady behaviour of the cited main statistics declines when there is evidence of climate change (Milly et al., 2008; Pulido-Velázquez et al., 2015).

Due to this complexity in evaluating aquifer recharge, and taking into account that its direct measure is often unreliable over large spatial scales, several techniques have been developed to evaluate aquifer recharge at different temporal and spatial scales, ranging widely in complexity and cost (Lerner et al., 1990; Scanlon et al., 2002). Recharge estimates can be classified according to the hydrological zone to which recharge refers (soil, vadose zone, and saturated zone) and the technique employed (physical, tracer, numerical modelling, and empirical) (Lerner et al., 1990; Scanlon et al., 2002, 2006; Coes et al., 2007; McMahon et al., 2011). On aquifer or catchment scales, water-balance techniques applied in the soil and in the vadose zone provide PAR estimates while tracer techniques, hydrodynamic methods based on Darcy's Law, and groundwater numerical models applied in the saturated zone provide NAR estimates (Lerner et al., 1990; Batelaan and de Smedt, 2007; Alcalá and Custodio, 2014).

For large-scale applications, geographical information system (GIS) can be coupled with lumped and distributed hydrological models to determine the spatial distribution of PAR or NAR (Barthel 2006; Minor et al., 2007; Batelaan and de Smedt, 2007; Pulido-Velázquez et al., 2015). Several examples combine different techniques to establish the different timing of PAR and NAR associated to the use of different techniques at different spatial scales (Nolan et al., 2007; Coes et al., 2007; Alcalá et al., 2011; McMahon et al., 2011).

The choice of one of these techniques depends on the objective of the study and the available data (Lerner et al., 1990; Scanlon et al., 2002; Islam et al., 2016). In this paper, the selection was based on the available distributed historical information about climatic variables (Spain02 project; Herrera et al., 2016) for PAR and existing databases for NAR (Alcalá and Custodio, 2015) in continental Spain. We will propose to apply an empirical modeling approach to assess yearly recharge for future potential climate scenarios in large-scale areas, such as Continental Spain.

The impact of climate change scenarios on Groundwater is a topic that has produced a continuous interest in the research community since 1990s (cf. Vaccaro (1992), Edmunds and Gaye (1994), Bouraoui et al. (1999), Eckhardt and Ulbrich (2003), Chen et al. (2004), Scibek and Allen (2006), Jyrkama and Sykes (2007)). In recent years the number and relevance of the studies has shown a sharp increase (cf. Di Matteo et al. (2011), Green et al. (2011), Treidel et al. (2012), Taylor et al. (2013), Kløve et al. (2014), Cotterman et al. (2017), Di Matteo et al. (2017), Gemitzi et al. (2017), Huang et al. (2017), Kidd (2017), McIntyre (2017)). Regarding the spatial scale, most of the studies assessed the impacts of climate change on a specific groundwater flow system (Dragoni and Sukhija, 2008; Molina et al., 2013; Pulido-Velazquez et al., 2015), while a few encompassed regional groundwater flow systems. Impacts on groundwater were considered in some basin-scale studies (e.g., Pulido-Velazquez et al. (2011), Herrmann et al. (2016), Escriva-Bou et al. (2017)) as well as for countries (Polemio, 2016) or entire continents (Earman and Dettinger, 2011; Panwar and Chakrapani, 2013; Adhikari et al., 2015; Hartmann et al., 2015).

In this paper we propose a new systematic method to assess yearly impacts of future potential climate change scenarios on net aquifer recharge (NAR) in large scale areas. Future potential climate scenarios are generated with a non-equifeasible ensemble of downscaling projections coming from different RCMs simulations. These scenarios are propagated with a new distributed empirical recharge model to estimate NAR from climatic fields. It has been applied in Continental Spain, an extensive and varied territory where no previous research work of this type has been performed. The results, which intend to be indicators of potential future plausible scenarios, are obtained under a set of hypotheses that are listed and discussed within the paper.

This paper is organized as follows. Section 2 describes the case study and available data. Section 3 presents the method used to assess potential impacts of future climatic scenarios on NAR. Section 3.1 defines an empirical precipitation-recharge model to simulate hydrological impacts from climatic variables (P, T). Section 3.2 describes the generation of future potential climatic scenarios. Section 3.3 describes the assessment of climate change impacts by simulating future potential climatic scenarios within a previously calibrated recharge model. Section 4 shows the results and discusses them. Finally, Section 5 presents the main conclusions.

## 2. Materials: description of the case study and available data

### 2.1. Case study: continental Spain

Continental Spain, lying between latitudes 36° and 44°N (Fig. 1), occupies most (493,519 $km^2$) of the Iberian Peninsula, the rest belonging to continental Portugal. A large proportion of the territory is occupied by the relatively high-elevation plains (*mesetas*), which lie at about 900 m a.s.l. in the northern half of the country and about 700 m a.s.l. in the southern half; the mountain ranges that enclose them may exceed 2500 m of elevation. The mesetas are characterised by a continental climate (MIMAM, 2000), which means hot, dry summers and cold, relatively wet winter-spring seasons.

Due to its varied geology, continental Spain has many relatively small yet high-yielding aquifers. The most important aquifers lie in Plio-Quaternary sedimentary formations in the large river valleys, and the quite extensive but compartmentalized Triassic to Tertiary carbonate massifs (Fig. 1). The former consist of groundwater bodies surrounded by mountain ranges, small alluvial and piedmont units, and deltaic formations on infilled estuaries in coastal areas. Carbonate massifs are common, occurring in quite extensive but compartmentalised areas along the northern, eastern, and southern mountain ranges (IGME, 1993). In addition, the weathered and fissured granite and Palaeozoic shale formations in the northern, southern, and north-eastern mountain ranges contain small aquifers of local significance. The wide lithological, orographic, edaphic, and climatic diversity of continental Spain gives rise to a wide range of conditions for net aquifer recharge (NAR) (Alcalá and Custodio, 2014, 2015).

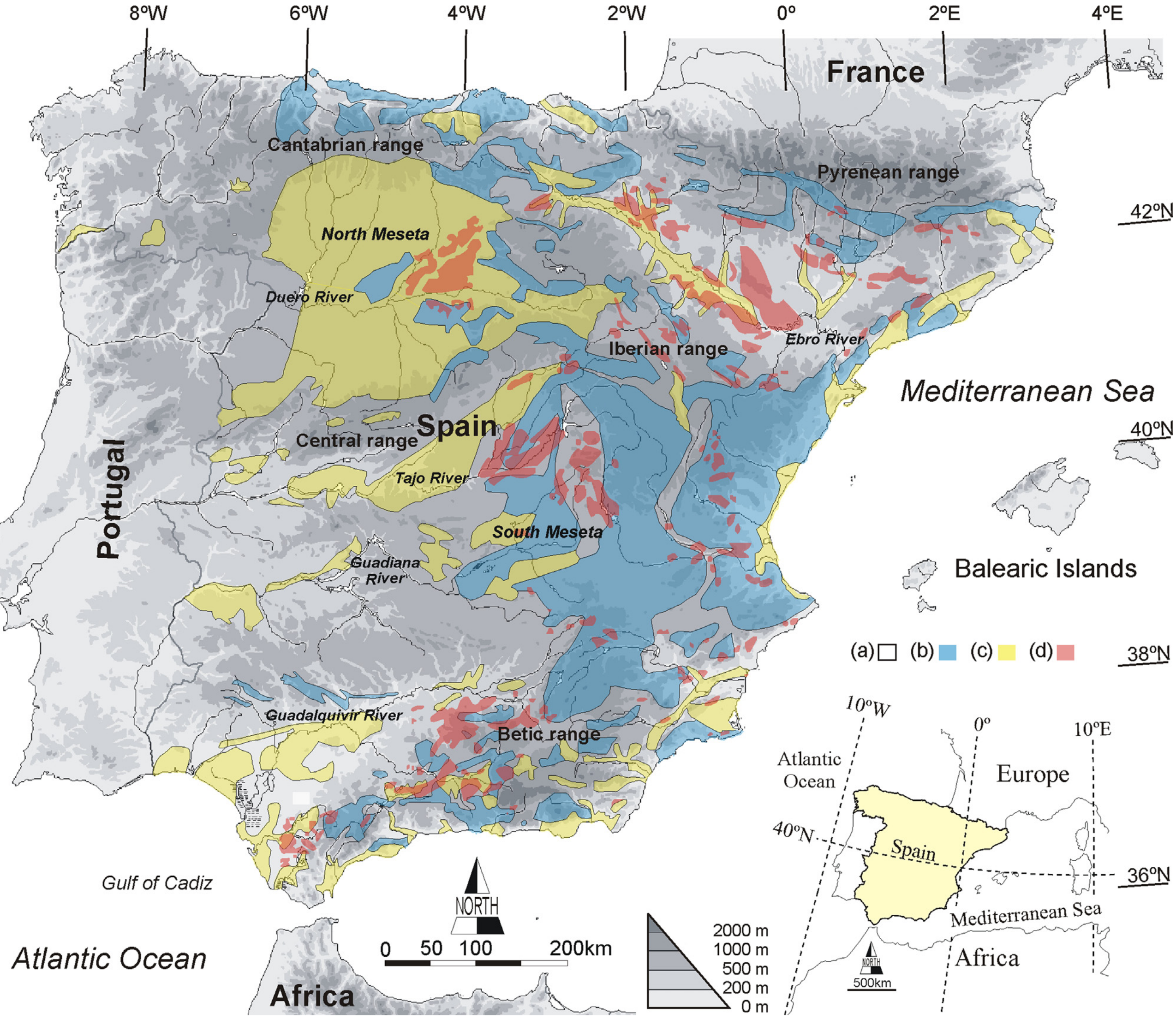


**Fig. 1.** Map of continental Spain, showing the main mountain ranges and hydrographic basins, and the hydrogeological behaviour of geological materials according to permeability type (IGME, 1993), modified from Alcalá and Custodio (2014): (a) low to moderate permeability pre-Triassic metamorphic rocks, granitic outcrops, and Triassic to Miocene marly sedimentary formations; (b) moderate to high permeability Palaeozoic to Tertiary carbonates; (c) moderate to high permeability Plio-Quaternary detritic materials; and (d) Triassic to Miocene evaporitic outcrops.

### 2.2. Historical climatic data

For the period 1976–2005, historical climatic (precipitation and temperature) time series were taken from the Spain02 project (Herrera et al., 2016), which includes a large database of meteorological data covering continental Spain. Precipitation (P) and temperature (T) show significant spatial heterogeneity due to the very different climatic conditions (Fig. 2). Mean P ranges from 2000 mm year$^{-1}$ in the northern mountainous areas, to about 500–600 mm year$^{-1}$ over the northern *meseta*, and 380–500 mm year$^{-1}$ in the southern *meseta* (Fig. 2a). In the semiarid south-eastern coastal areas and north-eastern inland areas, P is around 300 mm year$^{-1}$ or less, and sometimes as low as 180 mm year$^{-1}$ (MIMAM, 2000). Precipitation occurs mainly in late autumn and winter (November to March), associated with the circulation of cold air masses from the North Atlantic Ocean and deep pressure lows that travel eastwards and generate an inflow of air masses from the Subtropical Atlantic Ocean (Trigo et al., 2004). The eastern coast of Spain may also receive precipitation from humid air masses over the western Mediterranean Sea, especially in late summer and autumn, which generally do not penetrate far inland (Martín-Vide and López-Bustins, 2006). The annual mean T varies from 4.6 to 21.1 °C (Fig. 2b) with minimums in January and maximums in August; the daily T amplitude on a year may be as high as 50 °C in the southern *meseta* and river valleys. There is a pronounced gradient of T with elevation in mountain areas, thus favouring the seasonal snow-melting contribution to surface and groundwater bodies (MIMAM, 2000).

### 2.3. Historical recharge data

The CMB method was recently used for determining spatial mean NAR from precipitation and its uncertainty over continental Spain, by assuming long-term steady conditions of the CMB variables: atmospheric chloride bulk deposition, chloride export flux by runoff, and recharge water chloride content (Alcalá and Custodio, 2014, 2015). Other sources of natural recharge such as groundwater transferences among aquifers, external runoff contribution, and snow melting coming from others areas were not considered (Alcalá and Custodio, 2014, 2015). Alcalá and Custodio (2014, 2015) analysed the influence of hydraulic properties (permeability and aquifer storage) of different aquifer lithologies on

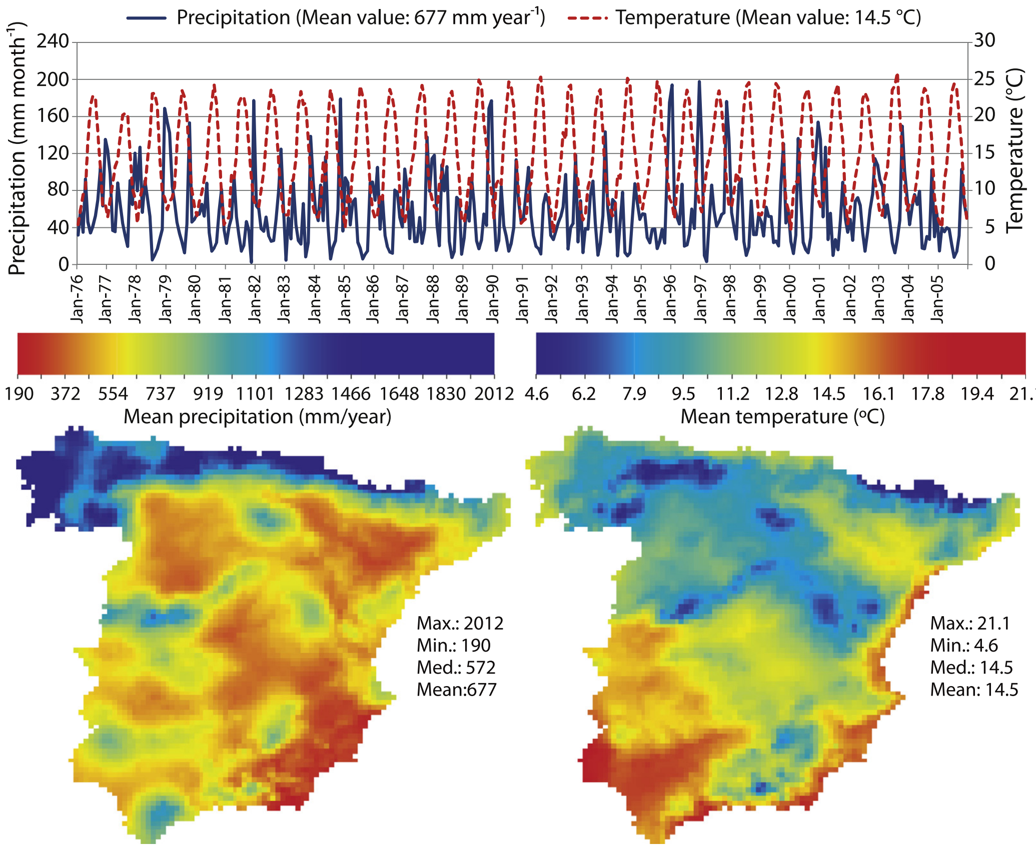


**Fig. 2.** Spatio-temporal distribution of historical mean (a) precipitation (mm year$^{-1}$) and (b) temperature (°C) in continental Spain during the reference period (1976–2005).

NAR estimates. For local usage, the hydrological meaning and reliability of distributed NAR was determined by comparing them with local, assumed trustable NAR values. The CMB variables were regionalised using ordinary kriging at the same 4976 nodes of a 10 km × 10 km grid to estimate a mean NAR value in each grid node. Two main sources of uncertainty affecting recharge, induced by the inherent natural variability of the variables and from mapping of the CMB variables, were identified and estimated (Alcalá and Custodio, 2014). While uncertainty from mapping may be reduced with better data coverage, the part of the natural uncertainty inferred by the variable length of yearly data series was corrected by comparing them to existing long time series. A data-correction procedure was implemented to improve mean annual NAR and its natural uncertainty deduced from variable-length data series (Alcalá and Custodio, 2015).

The critical balance period to reach comparable steady CMB averages and uncertainties was defined as around 10 years. This period coincides with the decadal global climatic cycles acting over the Iberian Peninsula, with imperfect ∼5-year positive and negative phases that follow the North Atlantic Oscillation trend

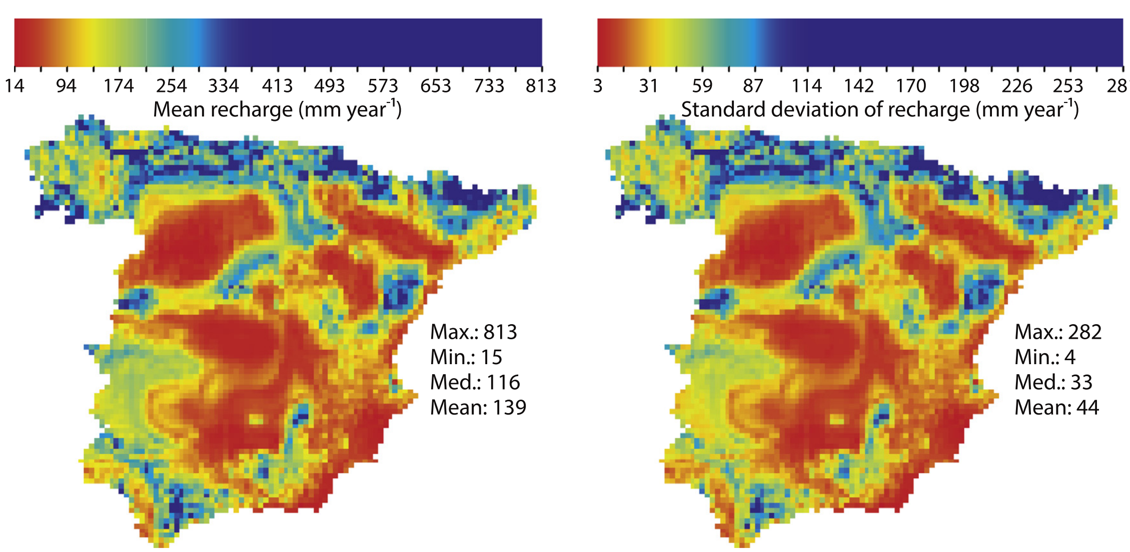


**Fig. 3.** Historical net aquifer recharge (NAR) from precipitation over continental Spain from the CMB method application for the period 1996–2005, after Alcalá and Custodio (2014, 2015): (a) annual mean NAR (mm year$^{-1}$) and (b) standard deviation of annual mean NAR (mm year$^{-1}$).

**Table 1**
Regional Climatic Models (RCMs) and General Circulation Models (GCMs) considered for simulations.

| RCMs \ GCMs | CNRM-CM5 | EC-EARTH | MPI-ESM-LR | IPSL-CM5A-MR |
|---|---|---|---|---|
| CCLM4-8-17 | X | X | X | |
| RCA4 | X | X | X | |
| HIRHAM5 | | X | | |
| RACMO22E | | X | | |
| WRF331F | | | | X |

(Hurrell, 1995; Trigo et al., 2004). Taking into account that (1) a minimum 10-year balance period is needed for reliable steady evaluations; and (2) the CMB databases covered preferably the period 1994–2007, the historical 1996–2005 period covering a 10-year long NAO climatic cycle with two successive 5-year long dry and wet phases was selected. Corrected CMB averages and natural uncertainties were regionalised. Mean annual NAR varied from 14 to 813 mm year$^{-1}$, with 90% ranging from 35 to 300 mm year$^{-1}$ (Fig. 3a), and the standard deviation of mean annual NAR varied from 4 to 281 mm year$^{-1}$ (Fig. 3b).

### 2.4. Climatic model simulation data. Control and future scenarios

Several series of climatic data generated with different climatic model simulations performed in the CORDEX EU project (2013) were employed. The most pessimistic emission scenario of the project, Representative Concentration Pathways 8.5 (RCP8.5), was selected. The simulations selected include results from five RCMs (CCLM4-8-17, RCA4, HIRHAM5, RACMO22E, and WRF331F) nested inside four different General Circulation Models (GCM), as shown in Table 1.

Dimensionless spatial monthly mean relative differences between the control simulation and the historical P time series for an average year over the reference period (1976–2005) were obtained by means of an equi-feasible ensemble of all RCMs simulations (Fig. 4). The relative difference distribution is negatively biased overall, with a central set of values in the ±0.7 range and extreme values of −0.87 in August and +1.33 in May. Except for October (with a slightly positive average relative difference) all months show negative differences, which justifies applying some correction to the time series obtained from the RCMs simulations. The negative differences reach −0.4 in March in the northern half of the territory, but not until July and August in southern and south-eastern highlands areas, characterised by dry continental and semiarid climates with evidence of active desertification (Martínez-Valderrama et al., 2016).

The summary of the spatial distribution of the mean impacts of climate change on P is represented using the dimensionless monthly relative differences between future (2016–2045) and control (1976–2005) time series by assuming equi-feasible ensembles of all RCMs simulations (Fig. 5). The relative difference distribution is positively biased overall, with central values in the ±0.1 range and extreme values of −0.44 in June and 0.2 in October. Except for January (with a slightly positive average relative difference), each month shows negative or close-to-average differences, with a very heterogeneous distribution. The negative relative differences decrease to below −0.1 in spring and summer (April to August) in the southern and south-western highlands.

## 3. Methods

The methodology used to assess impacts of future potential climatic change scenarios on aquifer recharge (NAR) from precipitation over continental Spain is described in three steps: (1) definition of an empirical distributed precipitation-recharge model; (2) generation of future potential time series of climatic variables (P, T) spatially distributed over the territory; and (3) assessment of future hydrological impacts on aquifer recharge.

### 3.1. Precipitation-recharge model

A distributed empirical precipitation-recharge model is defined by using the 10 km × 10 km grid, to generate NAR series from climate series in each grid cell. The model, instead of assessing recharge series by using exclusively P, which is an approximation commonly applied (Kirn et al., 2017, for example applying an infiltration coefficient to P) is defined from the historical PAR time series estimated as difference in P and actual evapotranspiration (AET) time series (PR recharge time series hereafter).

Taking the positive relationship of temperature (T) and AET into account (Arora, 2002; Gerrits et al., 2009), changes in T will determine the available non-evaporative fraction of P available for aquifer recharge. Other factors susceptible to control AET in the future are not considered. For instance, evaporation is expected to increase with warming temperatures, while transpiration may actually decline in some cases if the warming results from increased $CO_2$ due to $CO_2$ fertilization (Bazzaz and Sombroek, 1996; Ward et al., 1999; Green et al., 2007) and the vegetation cover transitions toward a more degraded condidion, as expected in the western Mediterranean region (Martínez-Valderrama, 2018) and other mid-terrestrial latitudes (Sun et al., 2017). On the other hand, warming climate can shift multiple days per year of snowfall to rain, potentially altering recharge.

Different non-global empirical models could be applied to estimate the historical AET from P and T time series (e.g., Turc (1954, 1961), Coutagne (1954), Budyko (1974); amongst others) as described in Beven (2007), Arora (2002), Gerrits et al. (2009), and España et al. (2013). In this study, the Turc (1954, 1961) model, in which annual AET depends on annual T and P, is applied in each grid cell as:

$$AET = \frac{P}{\sqrt{0.9 + \frac{P^2}{L^2}}} \quad (1)$$

where AET and P are in mm year$^{-1}$, and $L = 300 + 25\,T + 0.05\,T^3$ is a dimensionless parameter function of annual T.

The NAR series are obtained in each cell by applying a model whose target is to produce a perturbation of the historical PR series to obtain a new series whose mean and standard deviation is equal to the NAR series. The model is defined with a correction function that is calibrated forcing that the perturbation of the historical PR series produces a new series whose mean and standard deviation is equal to the historical NAR series data provided by Alcalá and Custodio (2014). The calibrated function will be applied to correct future PR series to obtain future NAR series assuming that the bias correction or correction function will not change in the future. The procedure involves the next steps:

(1) Average change of mean and standard deviation of the PR and NAR series for the same historical period:

$$\Delta\mu = \frac{\mu(NAR) - \mu(PR)}{\mu(PR)} \text{ and } \Delta\sigma = \frac{\sigma(NAR) - \sigma(PR)}{\sigma(PR)} \quad (2)$$

where $\Delta\mu$ is the change in mean and $\Delta\sigma$ is the change in standard deviation.

(2) Standardization of the PR series (historical and future)

$$PRn_i = \frac{PR_i - \bar{PR}}{\sigma_{PR}} \quad (3)$$

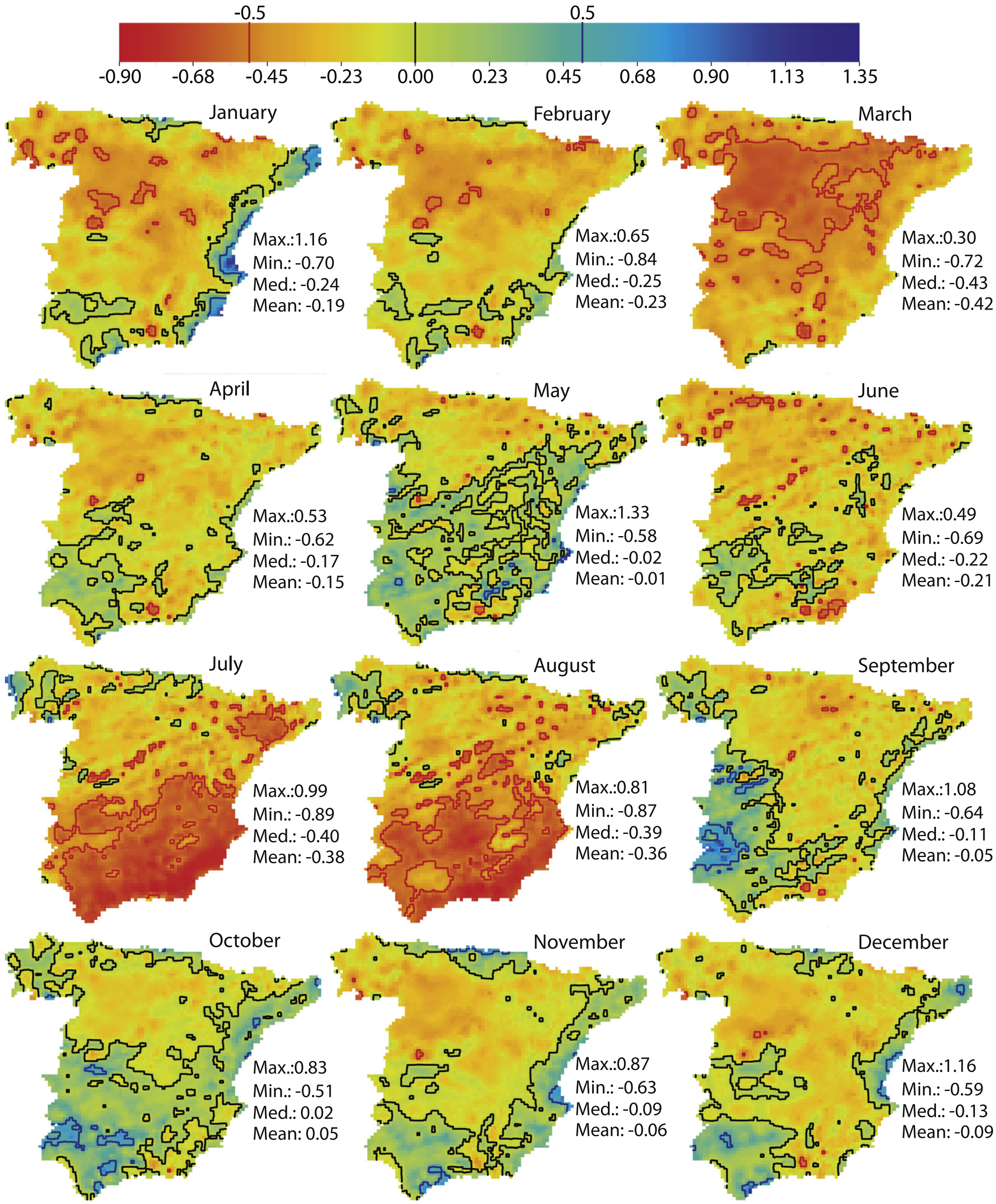


**Fig. 4.** Dimensionless spatial monthly mean relative differences between the control simulation and the historical precipitation time series for an average year in the reference period (1976–2005). The ±0.5 range is indicated.

(3) Generation of NAR series from PR series

$$NAR_i = \sigma_c \cdot PRn_i + \mu_c \quad (4)$$

where

$$\mu_c = \mu(PR) \cdot (1 + \Delta\mu) \text{ and } \sigma_c = \sigma(PR) \cdot (1 + \Delta\sigma) \quad (5)$$

When Eq. (4) is applied to the historical PR series the generated NAR series have the same mean and standard deviation to the historical NAR series of data provided by Alcalá and Custodio (2014). If it is applied to the future PR series future NAR series will be obtained assuming that the bias remain invariant in the future.

The NAR model was calibrated using PR recharge time series from historical climatic data (Section 2.2) and historical NAR data from the CMB method (Section 2.3) for the period 1996–2005. Two different hypotheses are assumed regarding the length of the PR recharge time series used to calibrate the precipitation-recharge model (the transformation function) (1) the same period of recharge time series (1996–2005; called mod_1996-2005); or (2) a longer historical period (1976–2005; called mod_1976-2005). This hypothesis assumes that the statistics (mean and standard deviation) of NAR time series from the CMB method for the period 1996–2005 and PAR time series generated from a longer historical period 1976–2005 do not differ substantially, and can be considered identical. This assumption is supported by assuming

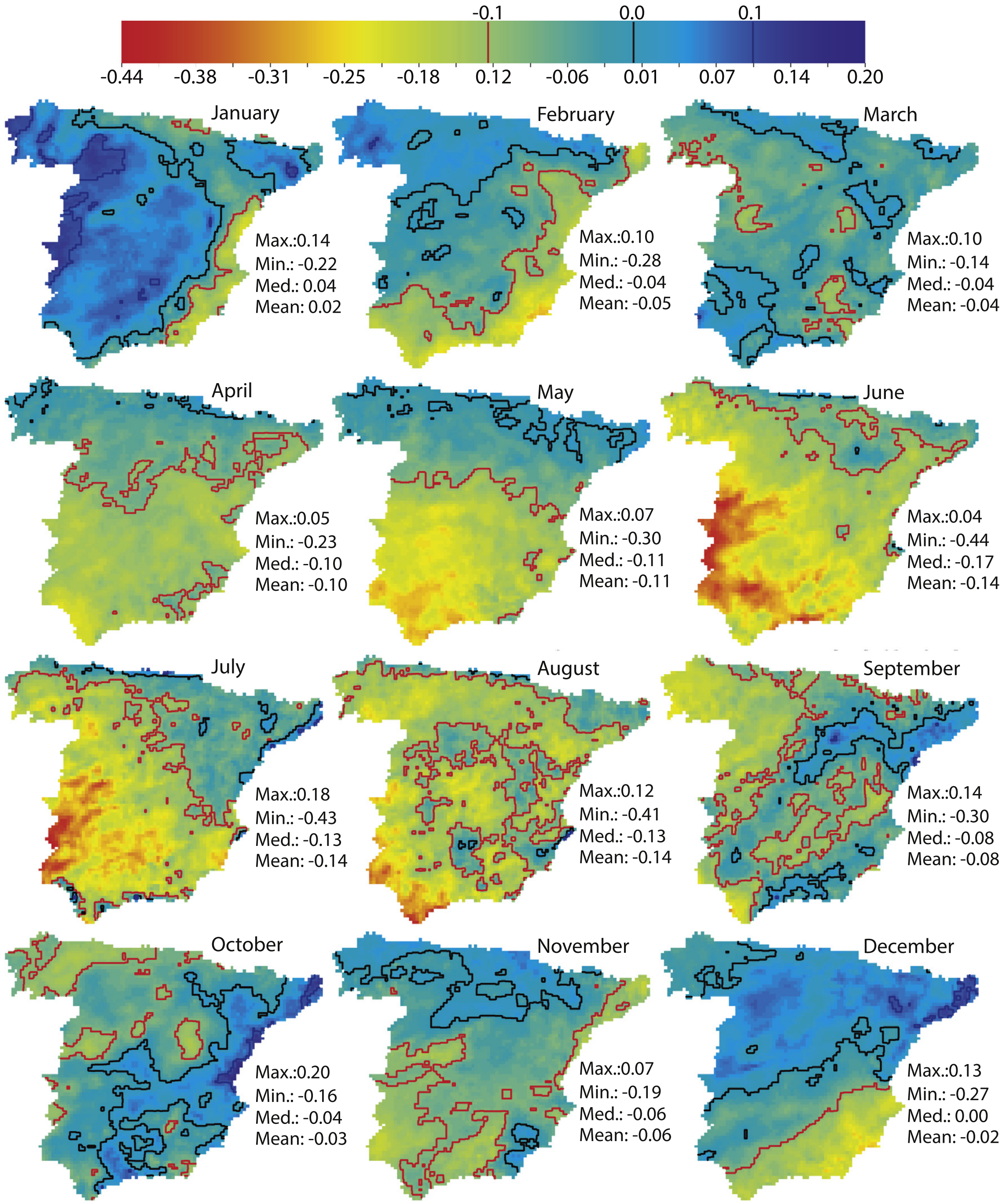


**Fig. 5.** Dimensionless spatial monthly mean relative differences between future (2016–2045) and control (1976–2005) precipitation time series. The ±0.1 range is indicated.

steady-state conditions of the mean and standard deviation of the balance variables determining the historical recharge when simulating the period 1976–2005 with both mod_1976-2005 and mod_1996-2005 models. The distributed mean annual recharge was 139 mm and 144.4 mm, respectively, thus the relative difference was less than 4% on average (Fig. 6). The maps show a quite similar spatial distribution despite the mod_1976-2005 providing a slightly more smoothed estimate with lower maximum values.

### *3.2. Generation of future potential climatic scenarios*

We introduce a method to generate potential future short-term-horizon (2016–2045) climatic scenarios from the historical data (1976–2005) and the available climatic models simulations performed in the CORDEX EU project (2013), taking the uncertainty linked to these future scenarios into account. For this, a multi-criteria analysis of the time series obtained by applying different correction techniques (bias correction and delta change) for downscaling the values obtained with the climatic model simulations was performed to identify the best fits to the historical data. Assuming equifeasible members or non-equifeasible members (see Christensen and Lettenmaier (2007), Lopez et al. (2009), Pulido-Velázquez et al. (2015)), different ensembles of the obtained time series are used to achieve more-representative future potential climate scenarios for assessing impacts on aquifer recharge.

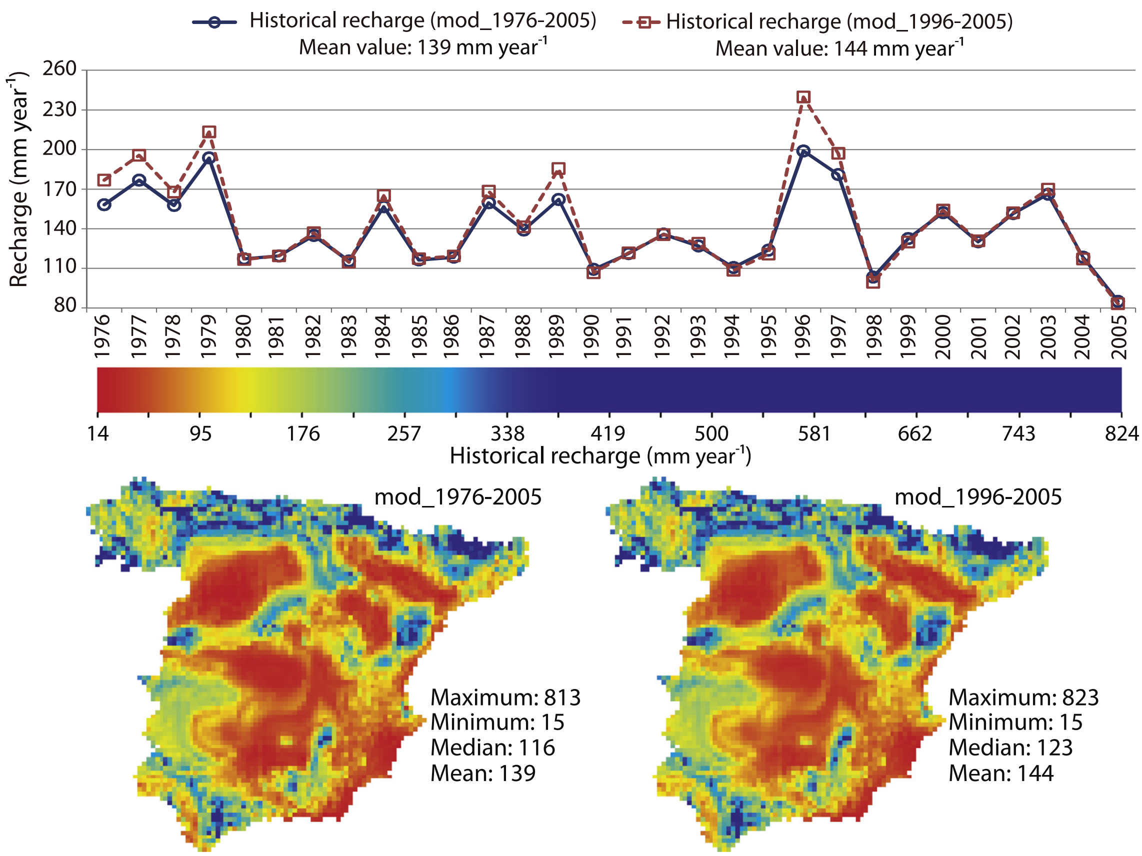


**Fig. 6.** Historical mean net aquifer recharge (mm year$^{-1}$) for the period 1976–2005 obtained when simulating with two different hypotheses regarding the length of the PE recharge time series used to calibrate the precipitation-recharge model: mod_1976-2005 and mod_1996-2005.

*3.2.1. Application of downscaling techniques: bias correction and delta change approaches*

Future scenarios of climatic variables for distributed PAR or NAR over a territory have usually been generated by applying statistical downscaling techniques to the outputs of climatic models (control and future scenarios), and taking the values of these variables in the historical period into account. RCMs provide dynamic approaches with a spatial resolution of tens of kilometres. They are nested inside General Circulation models that have coarser spatial resolution (hundreds of km of grid side). In most cases the statistics of the series generated by RCMs showed a bias regarding the 'real' values, and appropriate downscaling techniques are required to analyse impacts at the groundwater flow system scale. Depending on the problem, several downscaling techniques of varying complexity and accuracy (correction of first- and second-order moments, regression approach, quantile mapping, etc.) were applied by assuming different conceptual approaches, such as bias correction and delta change techniques (Räisänen and Räty, 2012).

Bias correction techniques aim to define a perturbation of the control time series to force some of their statistics closer to the historical ones. They assume that the bias between statistics of the model and data will remain invariant in the future (e.g. Haerter et al. (2011), Watanabe et al. (2012), Stigter et al. (2014)). The delta change techniques assume that the RCMs provide good assessments of the relative changes in the statistic between present and future, but they do not thoroughly assess the absolute values. They use the relative difference in the statistic of future and control simulations to perform a perturbation of the historical time series in accordance with these estimated changes (e.g. Pulido-Velazquez et al. (2011, 2015), Räisänen and Räty (2012)).

However, the spatio-temporal resolution between the historical and the control time series (from RCMs) often differs. Usually, the spatial resolution of historical datasets is greater than the spatial resolution of the RCMs dataset. So the transformations of both bias correction and delta change techniques indirectly produce downscaling approximations to the system (the spatial resolution of the RCMs is increased through the historical series in the case study). This is the reason they are commonly known as downscaling transformations.

In this research, two downscaling approaches were used, correction of first and second order moments, for both bias correction and delta change techniques. These were applied to all the RCMs simulations described in Section 2.2 (Table 1).

*3.2.2. Multi-criteria analysis of the main statistic*

A multi-criteria analysis analogous to those described in Pulido-Velazquez et al. (2011), Escriva-Bou et al. (2017), was used to identify the RCMs simulations that provide the best approximation to

**Table 2**
Inferior and non-inferior models in the multicriteria analysis.

| Eliminated? | RCM | GCM |
|---|---|---|
| No | CCLM4-8-17 | CNRM-CM5 |
| No | CCLM4-8-17 | EC-EARTH |
| No | CCLM4-8-17 | MPI-ESM-LR |
| No | HIRHAM5 | EC-EARTH |
| No | RACMO22E | EC-EARTH |
| No | RCA4 | CNRM-CM5 |
| No | RCA4 | EC-EARTH |
| No | RCA4 | MPI-ESM-LR |
| Yes | WRF331F | IPSL-CM5A-MR |

**Table 3**
Inferior and non-inferior combination of models and bias-correction techniques.

| Eliminated? | RCM | GCM | Technique |
|---|---|---|---|
| Yes | CCLM4-8-17 | CNRM-CM5 | First moment |
| No | CCLM4-8-17 | CNRM-CM5 | Second moment |
| Yes | CCLM4-8-17 | EC-EARTH | First moment |
| No | CCLM4-8-17 | EC-EARTH | Second moment |
| Yes | CCLM4-8-17 | MPI-ESM-LR | First moment |
| Yes | CCLM4-8-17 | MPI-ESM-LR | Second moment |
| No | HIRHAM5 | EC-EARTH | First moment |
| No | HIRHAM5 | EC-EARTH | Second moment |
| No | RACMO22E | EC-EARTH | First moment |
| No | RACMO22E | EC-EARTH | Second moment |
| No | RCA4 | CNRM-CM5 | First moment |
| No | RCA4 | CNRM-CM5 | Second moment |
| Yes | RCA4 | EC-EARTH | First moment |
| Yes | RCA4 | EC-EARTH | Second moment |
| No | RCA4 | MPI-ESM-LR | First moment |
| No | RCA4 | MPI-ESM-LR | Second moment |
| Yes | WRF331F | IPSL-CM5A-MR | First moment |
| Yes | WRF331F | IPSL-CM5A-MR | Second moment |

the main statistics (mean, standard deviation) of the historical time series. It aims to identify the best RCMs in terms of goodness of fit of the statistics of the control series to the historical ones. To assess it we define an error index (*ES*, see Eq. (6)) that is applied to the main statistics (mean and Standard deviation) for each RCM and climatic variable (precipitation and temperature).

$$ES = \frac{1}{N}\sum_{N}\left(\frac{S_c - S_h}{S_h}\right)^2 \tag{6}$$

where *ES* is the error of the considered statistic, *N* is the length of the statistical time series, *c* is the control simulation, and *h* is the historical. Table 2 shows eliminated and non-eliminated RCMs.

After assessing *Es* it in each cell we estimate the mean lumped value for our case study (Continental Spain), which will be employed to perform the multicriteria analysis. It intends to find models that were "inferior" to others in terms of fitting the historical dataset ('dominated solutions', in the terminology of multi-objective analyses). The models are then compared and those ones that were worse than any other model in all the statistics, i.e., strictly dominated are the "inferior" one.

It has been also applied to identify the best combination of models and bias correction techniques in terms of goodness of fit of the corrected control scenarios to the basic statistics of the historical time series. Due to the fact that most combinations of models and bias correction techniques provide good approximations to the first and second moments, a relative error threshold (percentage difference with respect to the historical statistics) was defined; only significant differences were used to decide when a corrected control is worse than other ones. Table 3 shows the inferior and non-inferior combinations of models and bias-correction techniques for a 3% threshold of the mean relative error.

### 3.2.3. Prediction ensembles to define more representative future climatic scenarios

Four options to define more representative future scenarios by applying different ensembles of the potential scenarios deduced from the available climatic models were considered. Two ensemble scenarios were considered by combining as equifeasible members all the future series (corresponding to different RCMs simulations) generated by bias correction (E1) or delta change (E2). Two other options were defined by combining only the non-inferior models using the 3% threshold [E3] (in bias correction approach) or the non-inferior combinations of model and correction technique [E4] (delta change techniques), by assuming that the inferior ones are untrusted.

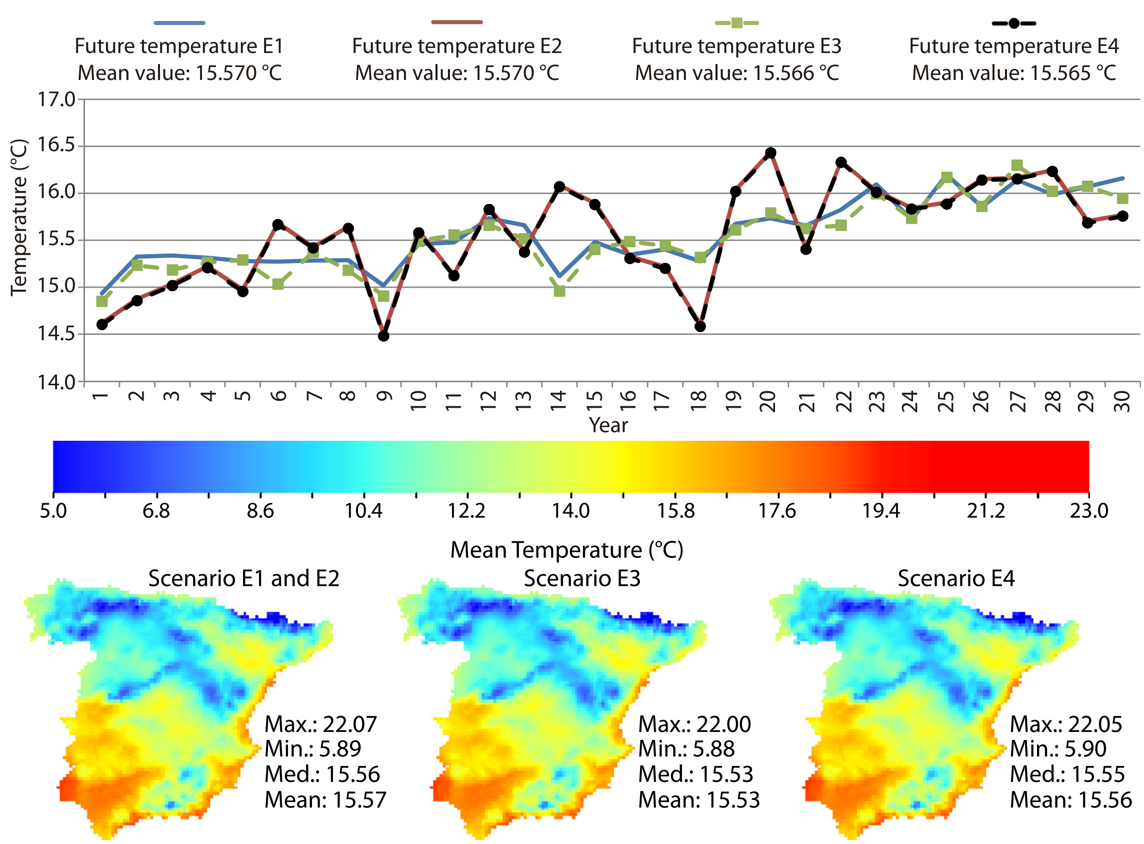


**Fig. 7.** Potential future mean temperature (°C) scenarios obtained with the four ensemble options (E1, E2, E3, and E4).

Despite the temporal series being different, the two equi-feasible ensembles E1 (applying bias correction techniques) and E2 (applying delta change techniques) produced identical future mean temperature maps (Fig. 7). There are very small differences in mean values between the equi-feasible projections and the two other alternatives. In terms of precipitation, there are very small differences between the two equi-feasible ensembles E1 and E2 due to a reduced number of negative values appearing in some cells when correcting using the second moment approach (Fig. 8). Larger differences appear between the mean values of these equi-feasible predictions and the two other alternatives, although they are not significant. Therefore, the sensitivity of the means of climatic variables to the hypothesis assumed to define the ensemble is quite low.

### 3.3. Assessment of future climate impacts on aquifer recharge

The analysis of climate change impacts required to simulate various climatic scenarios (Ei) within the precipitation-recharge models defined in Section 3.2. The results obtained are summarised and discussed in next section. Note that other variables affecting recharge, such as soil properties, vegetation patterns, and land use are considered steady, despite there being expected to change according to global climate driving forces and new human actions on a local scale that will be induced by adaptation to climate and water resource availability (Martínez-Valderrama et al., 2016, 2018). How these variables will change through time over the territory is not considered in this paper.

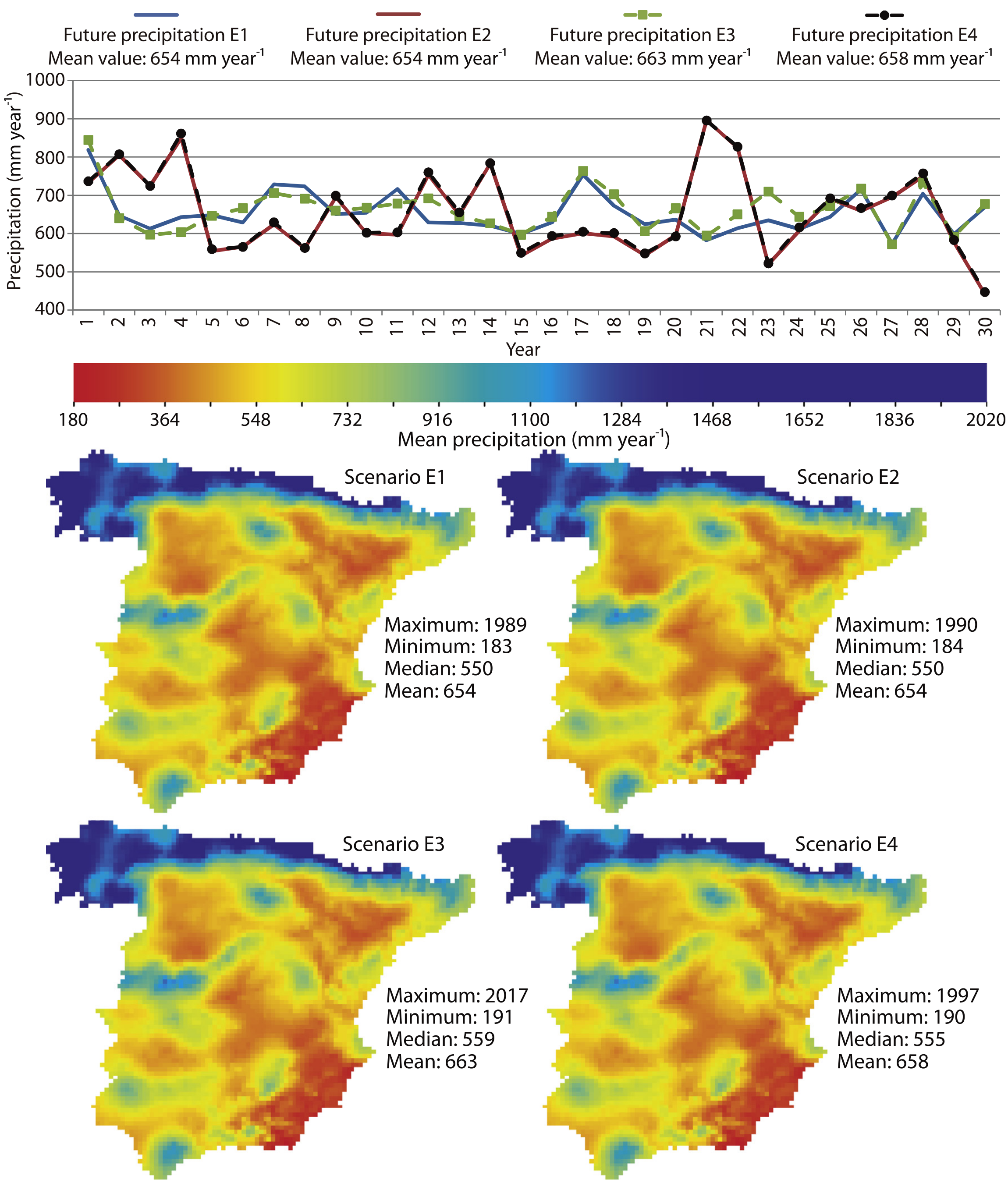


**Fig. 8.** Potential future mean precipitation (mm year$^{-1}$) scenarios obtained with the four ensemble options (E1, E2, E3, and E4).

## 4. Results and discussion

### 4.1. Future aquifer recharge scenarios

Eight potential future mean NAR scenarios for the period 2011–2045 were obtained by combining future potential climatic scenarios defined by the four ensemble options (E1, E2, E3, and E4) and two precipitation-recharge models (mod_1976-2005 and mod_1996-2005) (Fig. 9). As pointed out for the historical time series, the results obtained with the mod_1976-2005 are slightly smoother (with lower maximum values) than those ones obtained with the mod_1996-2005, as shown in the maps and graphs in Fig. 9. Note that significant differences in the temporal evolution of the annual future recharge time series are found when the assumed hypothesis are used. Scenarios E1 and E3 obtained by applying bias correction are similar to each other scenarios E2 and E4 obtained by using the delta-change perturbation technique. The recharge models used do not introduce large differences into the annual time series distribution, despite the mod_1976-2005 produces slightly more smoothed result with lower extreme values. The year-to-year distribution of recharge values for scenarios E2 and E4 is similar to that obtained by using the historical time series, though the mean value is slightly lower. This is due to the fact that the delta-change technique (E2 and E4) perturbs the historical time series while the bias-correction technique perturbs the future time series from the RCMs.

Nevertheless, in statistical terms, both the mean and the median values of the aggregate NAR for the various scenarios and recharge models applied do not differ substantially, varying in the 98.5–106.9 mm year$^{-1}$ and 120.8–128.3 mm year$^{-1}$ ranges, respectively. The spatial distribution of mean NAR for each of the four scenarios is also quite similar (Fig. 9). The sensitivity of the

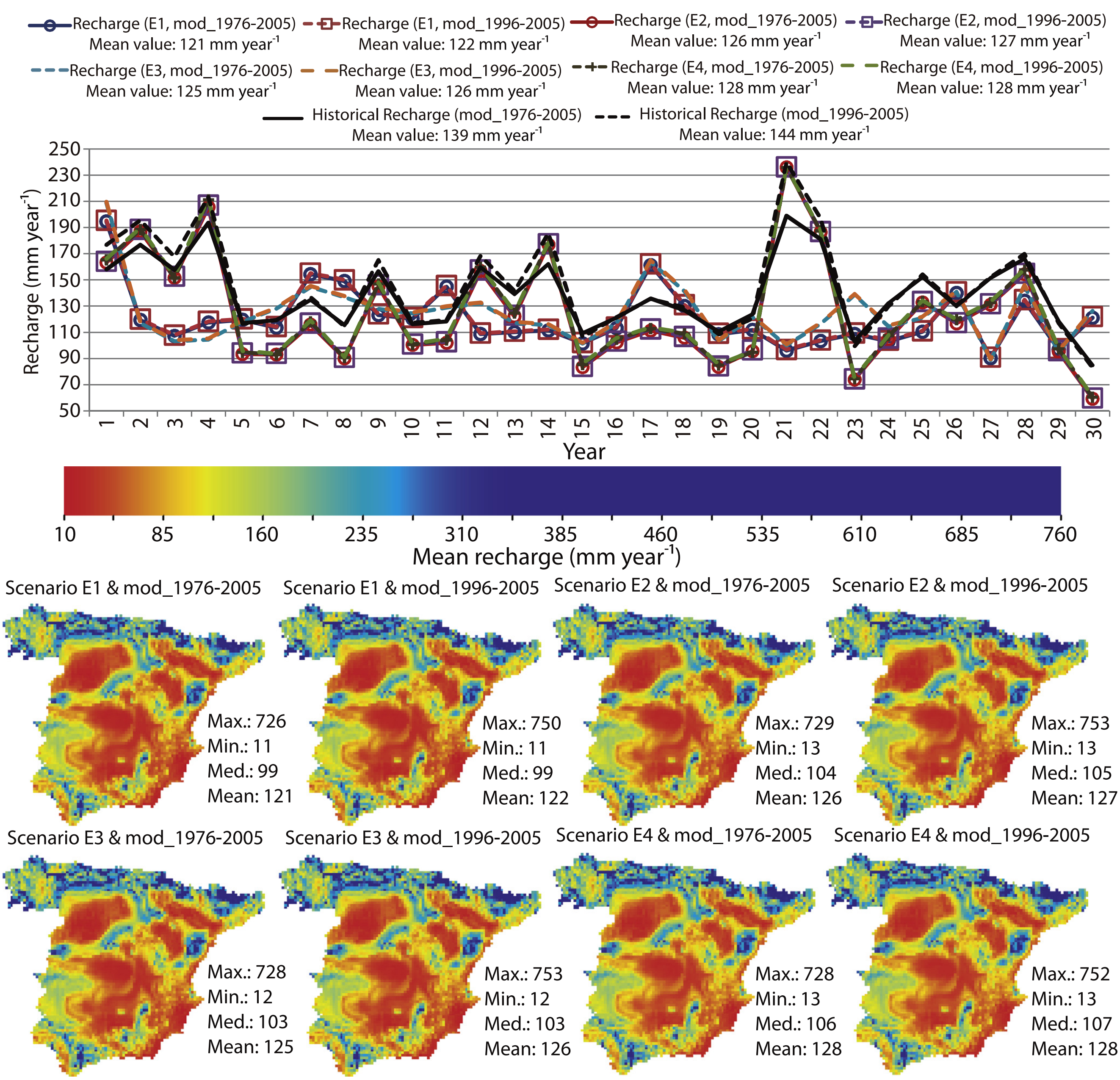


**Fig. 9.** Future potential mean net aquifer recharge (mm year$^{-1}$) scenarios for the period (2011–2045) by combining future potential scenarios defined by the four ensemble options (E1, E2, E3, and E4) and two recharge models (mod_1976-2005 and mod_1996-2005).

**Table 4**
Basic statistics of governing variables P, T, and R for the historical period, the four considered scenarios, and the two recharge models utilized.

| Statistic[a] | Historical period | | | | Scenario E1 | | | | Scenario E2 | | | | Scenario E3 | | | | Scenario E4 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | P | T | R[c] | R[d] | P | T | R[c] | R[d] | P | T | R[c] | R[d] | P | T | R[c] | R[d] | P | T | R[c] | R[d] |
| Minimum | 190 | 4.6 | 14 | 15 | 183 | 5.9 | 11 | 11 | 184 | 5.9 | 13 | 13 | 191 | 5.9 | 12 | 12 | 190 | 5.9 | 13 | 13 |
| Maximum | 2013 | 21.1 | 813 | 823 | 1989 | 22.1 | 726 | 750 | 1989 | 22.1 | 729 | 753 | 2017 | 22.0 | 728 | 753 | 1997 | 22.1 | 728 | 752 |
| Mean | 677 | 14.5 | 139 | 144 | 654 | 15.6 | 121 | 122 | 654 | 15.6 | 126 | 127 | 663 | 15.5 | 125 | 126 | 658 | 15.6 | 127 | 128 |
| Median | 572 | 14.5 | 116 | 123 | 550 | 15.6 | 99 | 99 | 550 | 15.6 | 104 | 105 | 559 | 15.5 | 103 | 103 | 555 | 15.6 | 106 | 107 |
| sd | 324 | 2.8 | 96 | 96 | 318 | 2.9 | 89 | 90 | 318 | 2.9 | 89 | 89 | 320 | 2.8 | 90 | 91 | 317 | 2.8 | 89 | 90 |
| cv[b] | 0.48 | 0.19 | 0.69 | 0.67 | 0.49 | 0.19 | 0.74 | 0.74 | 0.49 | 0.19 | 0.71 | 0.70 | 0.48 | 0.18 | 0.72 | 0.72 | 0.48 | 0.18 | 0.70 | 0.70 |

[a] P, E, and R in mm year$^{-1}$, and T in °C for minimum, maximum, mean, median, and standard deviation (sd) values.
[b] Dimensionless coefficient of variation, cv = sd/mean.
[c] mod_1976-2005.
[d] mod_1996-2005.

mean NAR and its distribution using both perturbation techniques (bias or delta change) and the ensemble hypothesis of the models (equi-feasible or not) is low; this is in agreement with what is observed by generating the future scenarios of P and T. The sensitivity of P and T maps to the recharge model employed (i.e., the transformation adopted) is also quite low; this is also expected given the small differences in mean in the simulations of the historical scenarios. A summary of basic statistics of governing variables P, T, and R for the historical period and future projections is included in Table 4.

The absolute differences of mean values between historical and future NAR time series obtained for the various scenarios oscillate between −11.5 and −22.8 mm year$^{-1}$ (Fig. 10). These figures highlight the differences between results obtained by using the various scenarios and recharge models. In terms of the means and medians, the differences are small, thus indicating that both time series are normally distributed and suitable for statistical comparisons. The model is more sensitive to which recharge model is applied (differences of 4.6 mm year$^{-1}$ and 3.8 mm year$^{-1}$ in the mean and median, respectively) than to the ensemble type (differences of 2.8 mm year$^{-1}$ and 2.6 mm year$^{-1}$ in the mean and median, respectively). There is intermediate sensitivity to the rescaling technique (differences of 3.9 mm year$^{-1}$ and 3.8 mm year$^{-1}$ in the mean and median, respectively). With respect to the extremes of mean P maps, the differences are small but the results are somewhat more sensitive to the rescaling correction technique (bias or delta change) than to the ensemble hypothesis (equi-feasible or not) or the recharge model applied (mod_1976-2005 and mod_1996-2005). Although this representation of absolute change also highlights that differences were almost unappreciable for the entire recharge dataset, the spatial distribution and statistics of values (Table 4) are very similar in all cases represented.

As far as standard deviation goes (Fig. 11), the ensemble scenarios are sensitive to the downscaling technique (bias or delta change). However, the sensitivity both to the recharge model and the ensemble hypothesis (equi-feasible or not) is low.

The results that would be obtained by using an equi-feasible ensemble of the eight scenarios in terms of mean NAR, standard

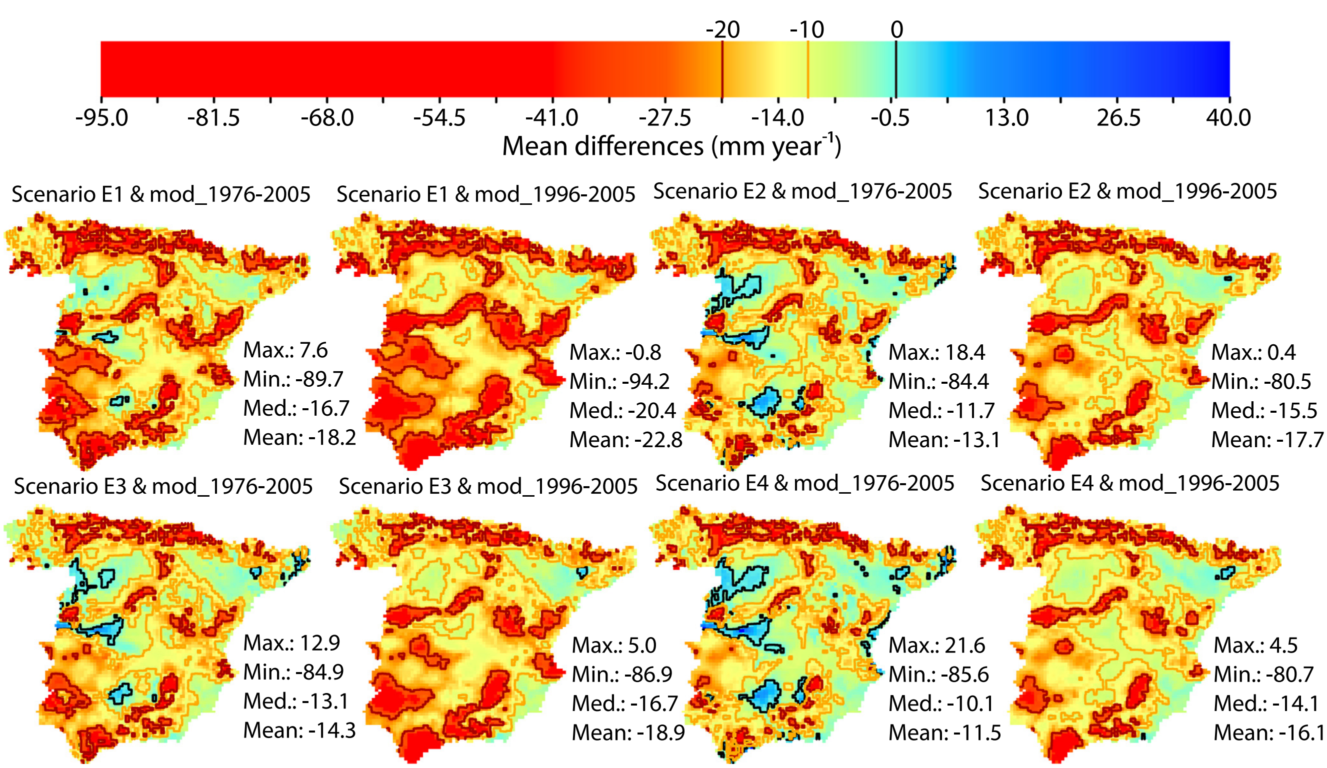


**Fig. 10.** Absolute differences in mean net aquifer recharge (mm year$^{-1}$) for the historical series under four different scenarios (E1, E2, E3, and E4) and recharge models (mod_1976-2005 and mod_1996-2005).

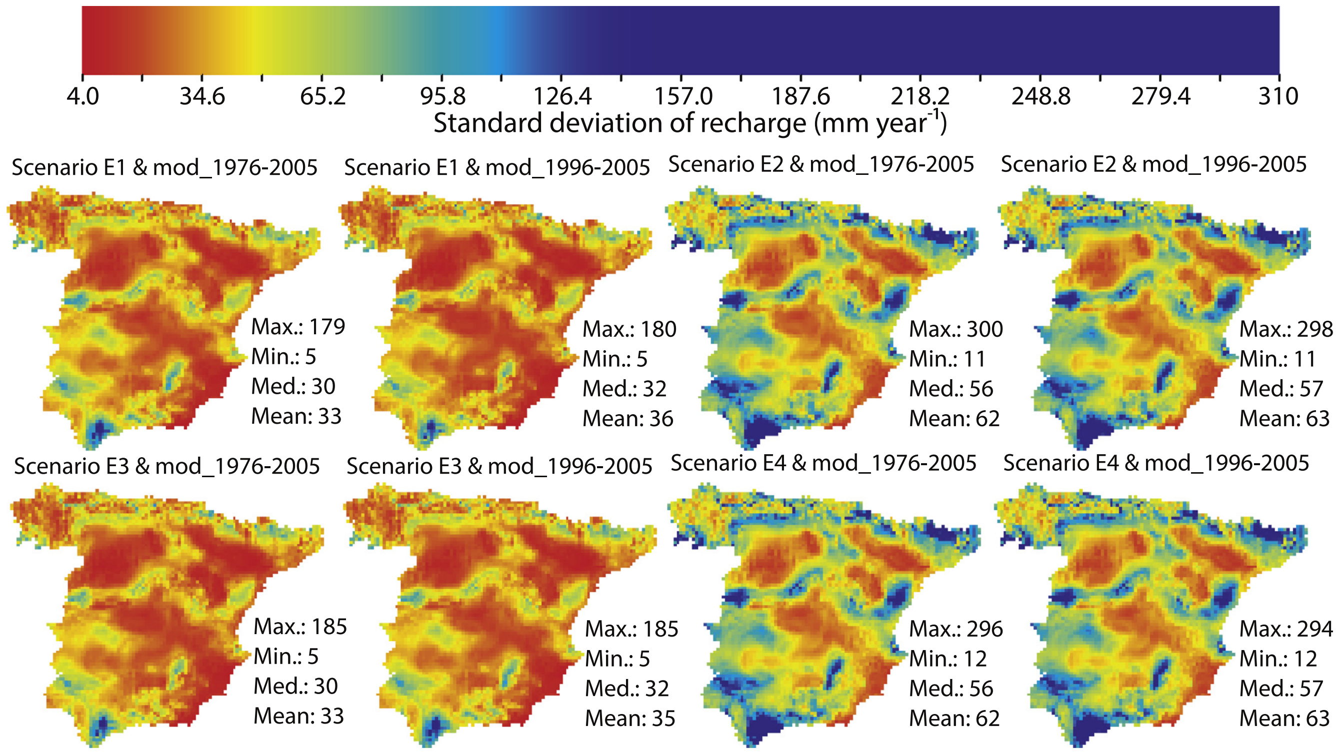


**Fig. 11.** Future potential scenarios of standard deviation of mean net aquifer recharge (mm year$^{-1}$) for the period (2011–2045) from combining future potential scenarios defined by the four ensemble options (E1, E2, E3, and E4) and two recharge models (mod_1976-2005 and mod_1996-2005).

deviation, and relative variation of the future mean NAR compared to the historical ones are showed in Fig. 12. One can see that although a small reduction in mean NAR is expected over 99.8% of continental Spain, there are two small north-eastern (600 km$^2$) and eastern (100 km$^2$) areas of the territory where a small increase is expected. A largest reduction in mean NAR in the centre and south-east of the territory is expected, dropping 28% in some areas. Only 6.6% of continental Spain corresponds to reductions of more than 20% in mean NAR. Nevertheless, 52.3% of the territory would suffer mean NAR reductions between 10% and 20%, while the reduction would be between 0% and 10% over 40.9% of the territory. In the case of the standard deviation on mean NAR, an increment of 41% on average is expected over 71.5% of the territory, being particularly marked in localized southern areas, with 36.7% of this area showing more than 50% increase. There would also be a significant reduction in the standard deviation in northern areas, with 6.9% of this area showing reductions greater than 30%.

Finally, relationships between the dimensionless relative differences in mean and standard deviation of mean NAR and some possible explanatory variables (elevation, latitude) is showed in Fig. 13. A poor linear correlation coefficient between relative differences and elevation is found, despite some general trends are observed. For instance, the range in relative differences in standard deviation of mean NAR decreases in the −0.3–0 range as elevation increases, especially above 1700 m a.s.l. in the main mountains ranges. While the standard deviation decreases at higher elevations, at lower elevations (0–200 m a.s.l.) a greater dispersion of the relative differences in standard deviation in the −0.3–0.8 range is found. The linear correlation coefficient between the relative differences and latitude is higher, of 0.30 for the mean and 0.56 for the standard deviation. The relative differences in the mean NAR increase with elevation, while the relative differences in standard deviation of mean NAR decrease with elevation. Other relationships with longitude were analyzed but, finding none, these analyses are omitted.

This work is the first one that assesses potential impacts of climate change on aquifer recharge in continental Spain. The limitations, uncertainties, and usefulness of the results are discussed below.

### *4.2. Limitations: assumptions, uncertainties, and usefulness of the results*

The assumption of hypothesis and simplifications to apply the method presented in this work introduces different kinds of uncertainty which propagate in the final results. The more relevant hypotheses have been grouped into the two main methodological steps used, as follows:

(1) Generation of future potential climatic scenarios
- Total precipitation was used instead of differencing between rainfall and snowfall. Although most of continental Spain receive snowfall rarely (if ever), there are some areas in Pyrenees and Sierra Nevada ranges that receive significant snowfall. A great uncertainty in those areas is expected because snowmelt acts as a more 'efficient' recharge agent than rainfall (Simpson et al., 1972; Winograd et al., 1998; Earman et al., 2006) and warming climate can shift multiple days per year of snowfall to rain, potentially altering recharge.
- The research focus on the analysis of future short-term-horizon (2016–2045). Other future horizons, such as mid-term and long-term scenarios have not been considered. For those mid-term and long-term scenarios, due to they are further away in time we will expect to have higher impacts on NAR. There should be also higher uncertainties for them.
- Only the most severe IPCC scenario was analysed (RCP 8.5) to assess the most pessimistic potential impacts on NAR in the future short-term scenario. The impacts of other poten-

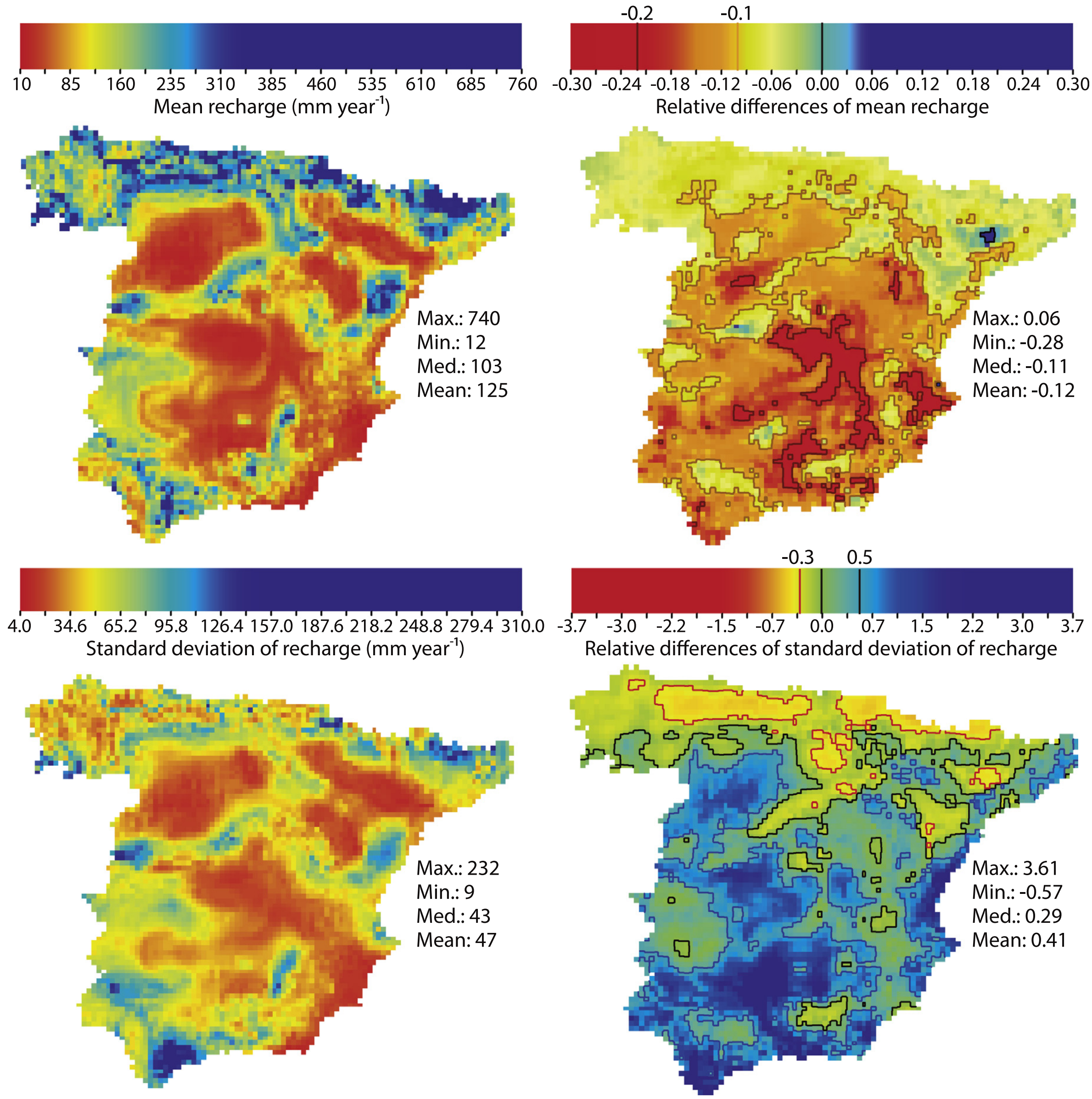


**Fig. 12.** Potential future mean net aquifer recharge (NAR) (mm year$^{-1}$), standard deviation of future mean NAR (mm year$^{-1}$), and dimensionless relative differences between historical and future scenarios (equi-feasible ensemble of the eight scenarios).

tial future scenarios (RCP2.6, RCP4.5, RCP6) on NAR should be less intensive.

- Two downscaling approaches (correction of first and second order moments) under two different hypotheses (bias correction and delta change techniques) were applied to generate future climatic series in accordance with RCMs simulations. Note that, depending on the problem and the target solution, several downscaling techniques of varying complexity and accuracy (correction of first- and second-order moments, regression approach, quantile mapping, etc.) can be applied by assuming different conceptual approaches, such as bias correction and delta change techniques (Räisänen and Räty, 2012). By combining both approaches we cover a wider range of solutions assessing the potential impacts of Climate Change, giving a better picture of the potential variability of the solutions.
- Potential plausible pictures of future climate scenarios are defined by combining information coming from different Regional Climatic Models (RCMs) and General Circulation models (GCMs). The 'ensembles' coalesce and consolidate the results of individual climate projections, thus allowing for more robust climate projections that are more representative than those based on a single model (Spanish Meteorologial Agency, AEMET, 2009).
- Two different hypotheses, equifeasible members or non-equifeasible members, were applied to define ensembles of the obtained future series for each RCM. They help to achieve more representative future potential climate scenarios for assessing impacts on aquifer recharge.

(2) Hydrological propagation of the climatic impact. Simulation of future climatic scenarios with a precipitation-recharge model.

- A simple empirical precipitation-recharge model has been adopted; whose inputs are P and AET, being the outputs NAR time series. We have not tested other hydrological models, for example, based on a more physically based or detailed representation of the processes involved in the hydrological balance (Eg. Snowmelt processes) and the

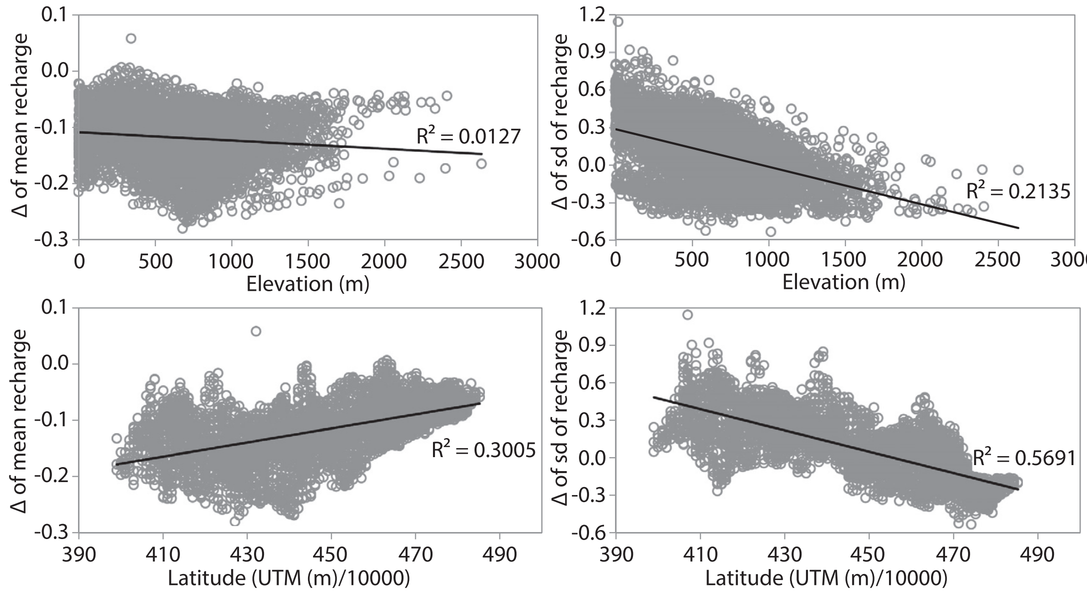


**Fig. 13.** Elevation and latitude vs. dimensionless relative differences between future and historical net aquifer recharge (mean and standard deviation).

geological structures. We assume that precipitation (P) and temperature (T) are the variables determining NAR, and their spatiotemporal variability determines the impacts of future potential climatic scenarios on renewable groundwater resources. We do not consider the changes in other variables affecting recharge, such as soil properties, vegetation patterns and land-use. They are considered steady, despite there being expected to change according to global climate driving forces and new human actions on a local scale that will be induced by human adaptation to climate and water resource availability (Martínez-Valderrama et al., 2016). The assess of these adaptation strategies developed to reduce the impacts on aquifer recharge is out of the scope of this research work.

- We assume that the climatic fields (P and T) taken from the Spain02 project (Herrera et al., 2016) and used as inputs of our model are good enough to approximate the historical climate. An assessment of the validation of some Spanish datasets, including Spain02, was recently carried out by Quintana-Seguí et al. (2017). The SPAIN02 dataset has already been employed in many research studies (Escriva-Bou et al., 2017; Pardo-Igurquiza et al., 2017).
- The Turc's model (1954, 1961) was applied to estimate AET. Its results depend on mean annual T and P. Different non-global empirical models could be applied to assess the historical AET from T and P time series. The applications of different methods would allow to assess uncertainties in this variable.
- The NAR series obtained by applying the chloride mass balance (CMB) method (Alcalá and Custodio, 2014, 2015) were used to calibrate the recharge model. The mean and standard deviation of the historical NAR for the period 1996–2005 were assumed representative of the steady-state condition, despite no longer than 40-year time series of the CMB variables are available in continental Spain to draw definitive conclusions (Alcalá and Custodio, 2014, 2015).
- The spatial resolution of the model, a regular 10 km × 10 km grid, is quite coarse because input data used to define the model were not available for smaller cells. Evertheless it allows to obtain a first approach to identify areas where more detailed analyses should be performed.

The results will be obtained under a set of hypotheses, and they are only indicators of potential plausible scenarios that may happen. Nevertheless, they give us an idea of the potential intensity of the climate change impacts under the most pessimistic emissions scenario in the analysed domain in a future short-term horizon (2016–2045). In spite of the uncertainties, the results also allow us to identify areas where the impact of climate change will be stronger. In these regions, there is the need for carrying out specific further research (using different detailed conceptual tools, etc) to provide a more detailed assessment of future values and uncertainties.

## 5. Conclusions

This work is the first one that assesses future potential impacts of climate change on aquifer recharge in continental Spain. A methodology is presented and used to estimate net aquifer recharge (NAR) over a regular 10 km × 10 km grid in two steps (1) generation of future potential climatic scenarios; and (2) hydrological propagation of the climatic impact by simulating future climatic scenarios with a precipitation-recharge model. The results, which are obtained assuming different hypotheses in each methodological step, are only indicators of potential plausible scenarios that may happen. They estimate the potential intensity of the climate change impacts for the horizon 2016–2045 under the most pessimistic emissions scenario. A reduction of mean NAR around 12% on average over continental Spain is deduced. A variable degree of NAR reduction over 99.8% of the territory is estimated; the reduction is quite heterogeneously distributed in line with the variety of conditions for aquifer recharge over continental Spain. The estimated standard deviation of mean NAR would increase by 8% on average in this future scenario. In spite of the uncertainties, the results are also useful to identify areas where the impact of climate change will be stronger. In these regions, we will need to perform more specific further research (using different detailed conceptual tools, etc) to provide a more detailed assessment of future values and uncertainties. The dependence of these changes regarding typical potential explanatory variables, such as elevation and latitude, was also analyzed. More significant relationships were found for the standard deviation that for the

mean NAR values. The magnitude and range of standard deviation decrease at higher elevations and lower latitudes.

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